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Effect of Granulated Blast Furnace Slag and fly ash addition on the strength properties of lightweight mortars containing waste PET aggregates

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ABSTRACT

In this work, the effect of Granulated Blast Furnace Slag (GBFS) and fly ash (FA) addition on the strength properties of lightweight mortars containing waste Poly-ethylene Terephthalate (PET) bottle aggregates was investigated. Investigation was carried out on three groups of mortar specimens. One made with only Normal Portland cement (NPC) as binder, second made with NPC and GBFS together and, third made with NPC and FA together. The industrial wastes mentioned above were used as the replacement of cement on mass basis at the replacement ratio of 50%. The size of shredded PET granules used as aggregate for the preparation of mortar mixtures were between 0 and 4 mm. The waste lightweight PET aggregate (WPLA)–binder ratio (WPLA/*b*) was 0.60; the water–binder (*w*/*b*) ratios were determined as 0.45 and 0.50. The dry unit weight, compressive and flexural–tensile strengths, carbonation depths and drying shrinkage values were measured and presented. The results have shown that modifying GBFS had positive effects on the compressive strength and drying shrinkage values (after 90 days) of the WPLA mortars. However, FA substitution decreased compressive and flexural–tensile strengths and increased carbonation depths. Nevertheless a visible reduction occurred on the drying shrinkage values of FA modifying specimens more than cement specimens and GBFS modified specimens. The test results indicated that, GBFS has a potential of using as the replacement of cement on the WPLA mortars by taking into consideration the characteristics. But using FA as a binder at the replacement ratio of 50% did not improve the overall strength properties. Although it was thought that, using FA as binder at the replacement ratio of 50% for the aim of production WPLA concrete which has a specific strength, would provide advantages of economical and ecological aspects.

1. Introduction

The using wastes in other industries has become one of the issues of researchers over the last few years, because of the advantages such as reducing the use of natural resources and the elimination of the wastes stored at waste storage areas without harming to the environment [1–5].

Construction industry is one of the areas of solid wastes can be used in large quantities. Especially large amounts of natural resources are used in concrete production. In addition, the production of Portland cement which is a basic component of concrete causes the greenhouses gases production which causes global warming and climate change [6]. For this reason, using wastes instead of cement and natural resources for concrete production will contribute to prevent the problems which are mentioned above.

Poly-ethylene Terephthalate (PET) which is one of the waste materials can be evaluated in concrete production. Amount of PET bottles which are used for packing water and various liquid foods increases drastically. In 2010, it was reported that PET bottles were produced about 150,000 tons in Turkey [7]. Due to the rapid increase on the use of PET bottles, solid waste problem is raised. In order to find a solution to this problem, in recent years some works on the re-using of PET wastes have been accelerated.

Fairly recent studies are available about the evaluation of the waste PET bottles in concrete production [8–15]. When the studies about using waste PET aggregates as lightweight aggregate for concrete and mortar production are examined; it is seen that waste PET granules have been used as partial or full substitutes for natural aggregate. Several strength and durability properties of specimens containing waste PET aggregate have been examined and usability for construction practice was investigated in these studies.

In previous study, Akcaozoglu et al. [8] investigated the strength properties of two group mortars which waste PET lightweight aggregates (WPLA) have been used as partial and full substitutes for sand. Granulated Blast Furnace Slag (GBFS) was used as the replacement of Normal Portland cement (NPC) on mass basis at

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the replacement ratio of 50%. The WPLA–binder (WPLA/*b*) and water–binder (*w*/*b*) ratios were 0.50 and 0.45, respectively. As a result of the study, the compressive strengths of mortar specimens were over 20 MPa, flexural–tensile strengths were over 4.7 MPa. The researchers concluded that, the produced specimens can be drop into structural lightweight concrete category in terms of unit weight and strength properties.

In a more recent study, Frigione [9] has been used waste PET particles as fine aggregate. The replacement ratio of WPLA was 5% and *w*/*b* ratios were determined as 0.45 and 0.55. The results indicated that, WPLA concrete showed similar workability characteristics with normal concrete. The compressive and splitting tensile strengths were lower than the reference concretes about 0.4% and 1.9%, respectively.

Choi et al. [10] have been used WPLA which was formed by waste PET particles coated with powder from river sand for mortar and concrete production. The compressive strength of mortar tended to decrease as the mixture proportion of WPLA increased. In comparison to the control concrete, the 28-day compressive strength of WPLA concrete decreased by 5%, 15% and 30%, with an increase of WPLA content of 25%, 50% and 75%, respectively.

Choi et al. [11] investigated WPLA microstructure which is obtained from waste PET bottles in other study. WPLA was made from the waste PET granules and GBFS on the surface of aggregates. The test results showed that, the specific gravity and the bulk density of WPLA were lower than the natural aggregate about 50%. The transition zone between the WPLA and the cement paste was expanded when compared with connection between the natural aggregate and cement. The compressive strength and the density of WPLA concrete reduced as the replacement ratio and *w*/*c* ratio increased. For instance, the 28-day compressive strength of WPLA concrete with the replacement ratio of 75% reduced about 33% compared to control concrete in the *w*/*c* ratio of 45%.

In another study, Albano et al. [12] investigated the mechanical behavior of concrete containing waste PET aggregate. The replacement ratios were 10% and 20% by volume, average sizes of the PET particles were 0.26 and 1.14 cm. The test results indicated that, when volume proportion and particle size of PET increased, compressive strength, splitting tensile strength, modulus of elasticity and ultrasonic pulse velocity decreased, and water absorption increased.

Marzouk et al. [13] used waste PET particles with maximum size was 5 mm as aggregate in concrete. It can initially be seen, when the amount of PET aggregates increased from 0% to 50%, the compressive strength of composites decreased slightly (about 16% in comparison with the reference mortar). The results showed that, if the replacement ratio exceeds 50%, the mechanical properties of composites fall strongly. However, when the volume of sand has been completely substituted by PET aggregates, the resultant composite developed rather high mechanical properties (a compressive strength greater than 3.5 MPa).

Gavela et al. [14] have been compared the strength properties of two different concrete composites; the first made with waste PET aggregates and the other made with Polypropylene (PP) aggregates. There were two replacement levels 20% and 30% by volume of aggregates. Laboratory tests showed that the 28-day compressive strengths of concrete containing 20% and 30% by volume of PET aggregates were 35.1 and 24 MPa, respectively. The flexural–tensile strengths were 4.79 and 3.27 MPa, respectively. The decrease in 28-days compressive and flexural strength of composites containing PET was similar to the composites containing PP. This means that, the polymer type does not influence the strength, only the percentage of replacement does.

In another investigation, Koide et al. [15] used PET and the other waste plastics together. The test results showed that, the produced lightweight concrete has been adequate high temperature resistance up to 60 °C and freeze–thaw resistance. PET content about 85%, Polypropylene and Polyethylene content about 15% were used in the plastic aggregate mixture. The 28-day compressive strength of specimens reached up to 20 MPa and the density of the concrete in the saturated surface-dry condition was about 1.8 g/cm^3.

The common thought in the investigations about WPLA mortar and concrete is that, the strength properties of specimens decreases due to the increasing waste PET aggregate amount in the mixture. However, it is indicated in these studies that, if the WPLA concretes and mortars have suitable replacement ratio, particle size and *w*/*c* ratio, they can be used for structural applications.

In this paper, WPLA was used as full substitute for sand in mortar composites. And also, each of GBFS and fly ash (FA) have been used as a partial cement on mass basis at the replacement ratio of 50% to obtain savings from the amount of cement and contribution to the properties of strength and durability of specimens.

GBFS and FA are two of binding properties materials which have been used as admixture to the cement for concrete production. GBFS is sufficiently able to react with calcium hydroxide to form calcium silicate hydrate (C–S–H) as a pozzolanic material [11]. It is known that, using GBFS improves the workability and reduces the bleeding of fresh mortar and concrete. Furthermore, GBFS is able to improve the strength of concrete, reduce the heat of hydration, permeability and porosity ratio and alkali-silica reaction [11,16–21]. FA which is a by-product of thermal power generation is a common used material for concrete production. Using FA as the admixture in concrete production has positive effects on the fresh and hardened concrete such as workability, strength, drying shrinkage, thermal properties and abrasion resistance [2,22–27].

One of the main aims of this study is evaluating the industrial wastes such as PET particles, GBFS and FA in the lightweight mortar production. The other important purpose is to investigate the effect of GBFS and FA which are quite commonly used in concrete and mortar containing natural aggregates on the strength properties of WPLA mortars. If produced WPLA mortar has satisfactory strength properties, it can be a good example for such sustainable construction materials.

2. Materials

The cement used was ASTM Type I Normal Portland cement (NPC 42.5 N/mm^2, 28-day compressive strength of 44.3 MPa). Initial and final setting times of the cement were 150 and 210 min, respectively. The specific gravity of the cement used was 3.09 g/cm^3 and Blaine specific surface area was 3220 cm^2/g.

GBFS was supplied from Iskenderun Iron–Steel Factory in Turkey. The hydraulic activity index of GBFS used was 84.5% [28]. The specific gravity and Blaine specific surface area were 2.81 g/cm^3 and 4250 cm^2/g, respectively.

FA used was obtained from Yumurtalik Sugozu Power Station located in southern Turkey. According to ASTM C-618 [29] it was classified as F class fly ash and the pozzolanic activity index was 78.8%. The specific gravity and Blaine specific surface area were 2.24 g/cm^3 and 3880 cm^2/g, respectively. Chemical oxide compositions of NPC, GBFS and FA are given in Table 1.

The waste PET bottles granules used as aggregate (WPLA) was supplied from SASA PET Bottles Plant, in Adana, in Turkey. It was obtained by picking up waste PET bottles and washing then crushing by granules in machines. Maximum size and specific gravity of WPLA were 4 mm and 1.27 g/cm^3, respectively. The grading of the WPLA is presented in Table 2.

3. Specimen preparation and testing methods

WPLA–binder (WPLA/*b*) ratio used in mortar specimen producing was 0.60, the water–binder (*w*/*b*) ratios were choosen as 0.45 and 0.50. NPC, GBFS and FA were used as binder. In M1 and M2 mixtures, only NPC was used as binder. In M3 and M4 mixtures GBFS was used as the replacement of cement, in M5 and M6 mixtures, FA was replaced the cement. The replacement ratio of GBFS and FA with cement was 0.50 by weight. The proportions of mortar mixtures produced in this study are given at Table 3.

Table 1
Chemical properties of NPC, GBFS and FA.

Binder	Oxide (%)									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	S	K_2O	Na_2O	LOI
NPC	20.23	5.78	4.07	61.95	2.94	2.66	–	0.87	0.11	0.72
GBFS	36.70	14.21	0.98	32.61	10.12	–	0.40	0.76	0.42	–
FA	56.91	21.85	6.52	3.33	2.57	0.26	–	0.99	0.48	2.36

Table 2
PET aggregate gradations.

Particle size range (mm)		PET (%)
d_{max}	d_{min}	
4	2	15
2	1	67
1	0.5	16
0.5	0.25	2
0.25	0	0
		100

Table 3
The proportions of WPLA mortar mixtures by weight (%).

Mixture name	Binder			WPLA	Water	Total
	NPC	GBFS	FA			
M1	47.6	–	–	28.6	23.8	100
M2	48.8	–	–	29.2	22.0	100
M3	23.8	23.8	–	28.6	23.8	100
M4	24.4	24.4	–	29.2	22.0	100
M5	23.8	–	23.8	28.6	23.8	100
M6	24.4	–	24.4	29.2	22.0	100

Table 4
Flow table values and dry unit weights of WPLA mortars produced.

Mixture name	Flow value (mm)	Dry unit weight (kg/m^3)		
		3 days	28 days	180 days
M1	140	1518	1490	1480
M2	125	1565	1550	1537
M3	138	1460	1443	1434
M4	120	1533	1502	1500
M5	170	1430	1375	1365
M6	150	1499	1443	1434

Prismatic specimens with 40 × 40 × 160 mm dimensions were prepared from fresh mortar mixtures and de-molded after a day. Later, they were cured in water at 22 ± 2 °C. The compressive strength and flexural–tensile strength of specimens were measured at 1, 3, 7, 28, 90 and 180 days. In addition, the dry unit weights, carbonation depths and drying shrinkage values of the mortar specimens were also measured. The specimens which were prepared for carbonation and drying shrinkage measurement were cured at 22 ± 2 °C with 65% RH in laboratory condition until the time of testing.

The compressive and flexural–tensile strength values of mortar specimens were measured by using the test methods according to TS EN 1015-11 [30]. The flexural–tensile strength measurements were performed on the three prismatic specimens by three points loading test. The compressive strength measurements were carried out using the broken pieces of the prism specimens obtained from flexural–tensile strength measurement. The drying shrinkage values of mortars were determined according to ASTM C-157 [31]. For the shrinkage measurement, two prismatic specimens with 25 × 25 × 285 mm dimensions were used. The length change measurements were carried out at every week until the 90 days, after 90 days they measured at every month until the 180 days.

4. Results and discussion

4.1. Flow value

There was no plasticizer added into the WPLA mortar mixtures. It can be seen from Table 4 that, the flow values of only cement mixtures and slag modified mixtures were close to each other. This situation may be based the reason about the densities of slag and cement were close to each other. Compared with the FA mixtures, at the same volume content, the WPLA mixtures containing GBFS showed less workability than the mixtures containing FA. This situation was probably due to the rough texture of GBFS [32,33]. The flow values of fly ash modified mixture were quite higher than cement mixtures and slag modified mixtures. The spherical shaped fly ash particles most probably contributed to the reduction in the internal friction in the mixture, and increase the flow ability of fresh concrete.

In addition, specific gravity of FA is lower than the specific gravity of PC and GBFS. The FA replacement with NPC results an increase in the paste volume of binder and filling the pores better. Therefore the mixtures including FA exhibit better flow properties [32–34]. The effect of increasing the flow ability of FA in natural aggregate concrete and mortars was similar to WPLA mortars.

4.2. Dry unit weight

Dry unit weights of WPLA mortars at 3, 28 and 180 days are presented in Table 4. The results showed that, the dry unit weights of all specimens have been decreased by the time-dependent. Because of the specific gravity of GBFS is lower than cement, the dry unit weights of WPLA mortars containing GBFS were lower than the WPLA mortars containing only NPC as binder. The dry unit weight values of mortars containing FA were quite lower than the others, since the specific gravity of FA is lower than cement and slag.

If the 28-day dry unit weights of specimens were determined, it was seen that the highest values of NPC, GBFS modified and FA modified specimens were 1550, 1502 and 1443 kg/m^3, respectively. The water–binder ratio of these specimens was 0.45. The decreasing water–binder ratio from 0.50 to 0.45 caused the increase of solid materials in the mixture; therefore unit weights of specimens with 0.45 w/b ratios were greater than 0.50 w/b specimens.

4.3. Compressive strength

The compressive strengths of WPLA mortars are presented in Table 5. (The range of variation of data was given in the parenthesis). The results shown are the mean made on three specimens

Table 5
Compressive strengths (MPa) of WPLA mortars produced.

Mixture name	Compressive strength (MPa)											
	1 day		3 days		7 days		28 days		90 days		180 days	
M1	7.8	(±0.3)	13.7	(±0.4)	19.1	(±0.5)	22.4	(±0.3)	24.8	(±0.4)	26.8	(±0.4)
M2	7.1	(±0.2)	15.5	(±0.4)	19.2	(±0.4)	23.6	(±0.1)	26.5	(±0.3)	28.0	(±0.2)
M3	4.2	(±0.2)	8.8	(±0.3)	13.9	(±0.4)	23.2	(±0.3)	26.2	(±0.3)	27.9	(±0.4)
M4	4.6	(±0.2)	9.9	(±0.3)	15.3	(±0.4)	26.0	(±0.1)	27.9	(±0.2)	30.6	(±0.4)
M5	1.3	(±0.5)	7.5	(±0.4)	9.2	(±0.3)	13.5	(±0.5)	18.2	(±0.4)	20.9	(±0.4)
M6	4.2	(±0.1)	7.4	(±0.4)	9.7	(±0.2)	15.1	(±0.1)	20.1	(±0.3)	23.1	(±0.3)

whose single values do not differ more than ±0.5 MPa from the mean reported in the Tables. It can be seen from Table 5 that, the compressive strength of specimens made with only NPC and made with NPC and GBFS together were very close to each other. But the compressive strength values of mortars containing FA were lower than the others. The compressive strength of NPC mixtures were 22.4 and 23.6 MPa; the compressive strength of GBFS mixtures were 23.2 and 26 MPa at 28 days. However FA mixtures developed low strength values about 13.5 and 15.1 MPa at 28 days.

The hydration of slag used as binder begins after the hydration of cement. Because slag needs for calcium hydroxide ($Ca(OH)_2$) and moisture which are occurred as a result of cement reaction to show its binding property. For this reason, the strength of slag modified concrete is lower than the strength of control concrete containing only cement in early age. However if it is cured adequately, its strength can be equivalent or higher than the control concrete in long term [16,33,35,36]. This result which is indicated in the literature is compatible with the slag modified WPLA mortars produced in this research. In general slag mortars showed lower compressive strength than cement mortars in early ages. But after 28 days, they caught the values of cement specimens and then exhibited higher compressive strength than cement specimens.

The strength development of concrete containing FA is slower than at first time, but it continues to gain strength in the long time; is a fact well known in the literature [24,25]. In general, available studies reported that FA used in concrete production about 10% and 20% causes an increase in compressive strength [37,38]. Similarly, Anwar and Adam [39] reported that, FA may be used between 15% and 25% ratios in order the increase the compressive strength of concrete. Chen and Liu [33] indicated that the compressive strength at 28 days reached the highest value when the amount of FA was 20%. However after this ratio it decreased due to the increase of the amount of FA. It was mainly because of the pozzolan reaction of FA is slow process at normal temperature. Considering both rheological and strength properties, authors did not suggest to add the FA to the LWAC alone. Tanyildizi and Coskun [40] obtained the highest strength value at the replacement ratio of 30%. In this study because of high FA replacement ratio (50%) was used, the specimens modified with FA did not reach the compressive strength values of cement specimens and slag modified specimens in both early and later ages.

Table 7
Carbonation depths (mm) of WPLA mortars produced.

Mixture	Carbonation depth (mm)				
	3 days	7 days	28 days	90 days	180 days
M1	0	0.6	1.6	3.5	6.5
M2	0	0.3	1.7	3.1	6.0
M3	0	1.2	3.0	5.1	9.3
M4	0	0.8	3.0	4.5	9.0
M5	0	1.1	4.1	7.4	12.0
M6	0.3	2.1	3.5	5.7	10.9

4.4. Flexural–tensile strength

The results of flexural–tensile strength tests which were conducted on WPLA mortars are presented in Table 6. (The range of variation of data was given in the parenthesis; the maximum deviation was ±0.5 MPa). The flexural–tensile strengths of the mixtures containing GBFS were close to the NPC mixtures, but similar to normal mortars or concretes they did not reach to flexural–tensile strength values of NPC specimens any day. The 28-day flexural–tensile strengths of NPC specimens and GBFS modified specimens were 4.0 MPa and over, FA modified specimens were 3.0 MP and over. The flexural–tensile strengths of mortars containing FA were lower than the others at all days (Table 6). This result was similar to the compressive strength results of WPLA mortars in this study.

4.5. Carbonation depth

The carbonation depths of WPLA mortars were measured by using Phenolphthalein solution. Phenolphthalein solution was applied on the fresh broken surfaces of the half pieces of prismatic specimens (40 × 40 × 160 mm) which were obtained from flexural–tensile strength test. After the solution applied to 40 × 40 mm dimensions area, carbonated outside areas remained colorless while non-carbonated internal areas turned purple color. The results are presented in Table 7 and Fig. 1.

It can be observed from Table 7 that, carbonation depths of WPLA mortars increased depending on increasing CO_2 amount penetrated into the specimens which increased in time. The mortars containing FA and the mortars containing GBFS had more carbonation depths than NPC mortars. The highest value was seen at the mortars modified with FA at all days.

Table 6
Flexural–tensile strengths (MPa) of WPLA mortars produced.

Mixture name	Flexural–tensile strength (MPa)											
	1 day		3 days		7 days		28 days		90 days		180 days	
M1	2.5	(±0.4)	3.3	(±0.5)	4.1	(±0.1)	4.3	(±0.5)	4.9	(±0.1)	5.8	(±0.2)
M2	2.0	(±0.4)	3.5	(±0.3)	4.0	(±0.4)	4.5	(±0.3)	5.2	(±0.2)	6.0	(±0.1)
M3	2.2	(±0.4)	2.6	(±0.3)	3.1	(±0.4)	4.0	(±0.1)	4.4	(±0.3)	5.0	(±0.4)
M4	1.8	(±0.2)	2.7	(±0.1)	3.3	(±0.5)	4.2	(±0.2)	4.6	(±0.4)	5.2	(±0.1)
M5	1.0	(±0.1)	1.8	(±0.4)	2.7	(±0.3)	3.0	(±0.3)	3.5	(±0.1)	4.0	(±0.2)
M6	1.3	(±0.2)	1.8	(±0.1)	2.6	(±0.3)	3.3	(±0.3)	3.7	(±0.1)	4.3	(±0.3)

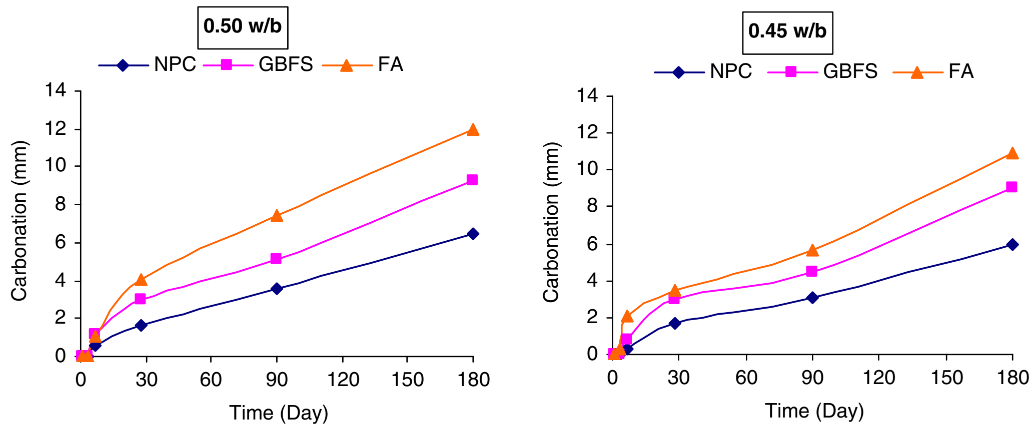

Fig. 1. Effects of GBFS and FA on the carbonation depths of WPLA mortars.

Table 8
Drying shrinkage values (%) of WPLA mortars produced.

Mixture name	Days															
	7	14	21	28	35	42	49	56	63	70	77	84	90	120	150	180
M1	0.09	0.14	0.16	0.16	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.18	0.21	0.23	0.23
M2	0.08	0.14	0.15	0.15	0.15	0.16	0.16	0.17	0.17	0.17	0.18	0.18	0.18	0.20	0.22	0.22
M3	0.10	0.15	0.16	0.16	0.16	0.16	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.20	0.21	0.22
M4	0.10	0.14	0.16	0.16	0.16	0.16	0.16	0.16	0.17	0.17	0.18	0.18	0.18	0.19	0.21	0.21
M5	0.09	0.12	0.13	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.14	0.15	0.15	0.16
M6	0.08	0.11	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.15	0.16	0.16

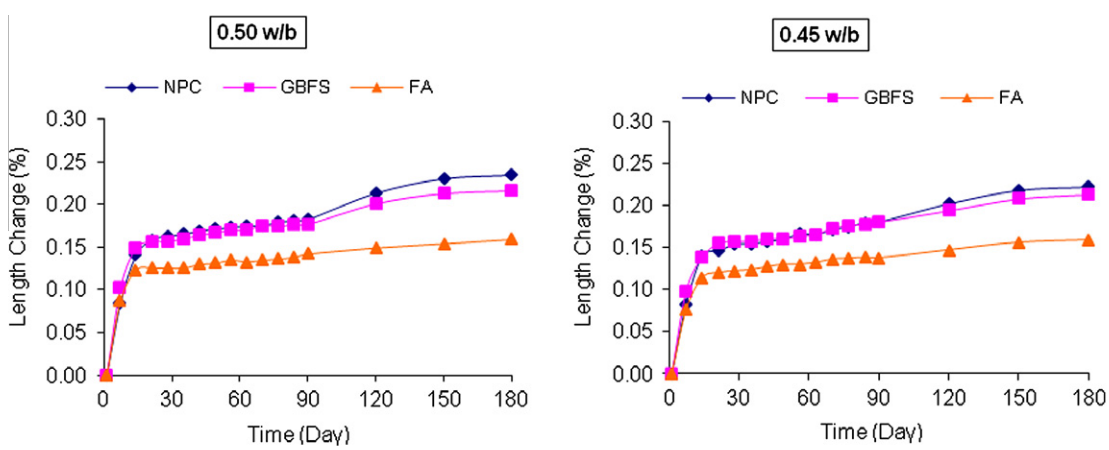

Fig. 2. Effects of GBFS and FA on the drying shrinkage of WPLA mortars.

When Fig. 1 is examined, it is seen that carbonation values of the specimens increased in time until 180 days. However, it is indicated in previous study which WPLA mortar specimens were produced by lower WPLA/*b* ratio (0.50) that, the carbonation behaviors of the mortars continued with a decreasing speed after 90 days [8]. From here it is thought that, the high WPLA/*b* ratio used in the mixtures in this investigation decreased workability and caused more porous structure. In this case, large amount of CO_2 penetrated in the mixtures from their pores which are open to the outside, and then carbonation depths of mixtures increased until the 180 days.

4.6. Drying shrinkage

The results of drying shrinkage or length change of WPLA mortar specimens are presented in Table 8 and Fig. 2. It can bee seen from Table 8 that, the shrinkage values of NPC specimens (M1 and M2) were 0.22% and 0.23%; the values of GBFS modified specimens (M3 and M4) were 0.21% and 0.22%; and the values of FA modified specimens (M5 and M6) were 0.16%, at 180 days. However, the 180-day drying shrinkage values of standard control normal weight mortar mixtures with 0.50 and 0.45 *w*/*b* ratios which were prepared for comparison purposes were 0.10% and 0.09%, respectively. According to these results it was seen that, the shrinkage values of WPLA mortars were quite higher than reference mortars with natural aggregates. (The standard deviations for M1 and M2 mixtures were 130% and 144%, for M3 and M4 mixtures were 120% and 133%, for M5 and M6 mixtures were 60% and 77%, respectively).

The main reason for this situation is thought to be due to the high dosage of cement mixture in WPLA mortars. Neville [32] indicated that, due to the low modulus of elasticity of lightweight aggregate the shrinkage values of lightweight concrete are high. The connection between plastic particles and the cement paste is known to be weak compared to the connection between natural aggregate and cement paste [8,9,14,15,41]. It is thought that, the mentioned reasons caused the high shrinkage values in WPLA mortars.

In this study which is performed on WPLA mortars, amount of cement in the mixture decreased to half due to the GBFS replacement with the replacement ratio of 50%. But shrinkage values decreased after 90 days. The shrinkage mechanism of the GBFS which is replaced with cement may be caused this result. Because, it is stated in the literature that, the shrinkage mechanisms of concretes containing GBFS is similar to concrete used NPC, and using GBFS causes very little effect on drying shrinkage of concrete [19,42]. When the graphics are analyzed, the specimens containing only cement and the specimens containing cement and slag together have almost the same shrinkage values of up to 90 days; after this day the shrinkage values of mortars modified with slag decreased compared to the cement specimens (Fig. 2). This situation continued up to 180 days. In other words, the slag admixture showed the shrinkage-reducing effect after 90 days.

Table 8 also shows that, drying shrinkage values of FA modified mortar specimens were close to NPC specimens and GBFS modified specimens at the beginning. However after 14 days, their shrinkage values were quite lower than the others. This situation continued until the last day measured values of shrinkage. The drying shrinkage of concrete containing FA is known to be low in the literature. The reduction in shrinkage due to the use of FA in mortar could be explained by the dilution effect of FA. Karahan [43] indicated that, the lowest shrinkage value of fly ash modified concrete was seen at the replacement ratio of 45%. In this study, fly ash used as the replacement ratio of 50% significantly reduced the drying shrinkage of WPLA mortars similar to mortars and concretes produced with natural aggregates.

5. Conclusions

The use of GBFS with the replacement ratio of 50% in waste PET lightweight aggregate (WPLA) mortars, reduced unit weight, increased compressive strength and reduced drying shrinkage after 90 days.

The use of FA at the same replacement ratio decreased significantly unit weight and drying shrinkage, improved flow value, but decreased compressive and flexural–tensile strength values compared to cement specimens.

Based on the mechanical strength measurement results, it can be concluded that GBFS, possessing the same characteristics of the experimented material, can be used in WPLA mortars up to 50% replacement of cement for increasing compressive strength, but using FA with the same ratio is not suitable for same purpose.

Both of GBFS and FA increased the carbonation depths of specimens. For this reason, carbonation reducing measures must be taken when using these mineral admixtures for WPLA mortar or concrete production with high ratios (50% and over).

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